Exploring the Third Dimension: Why Imaging Dark Energy Experiments Need DESI

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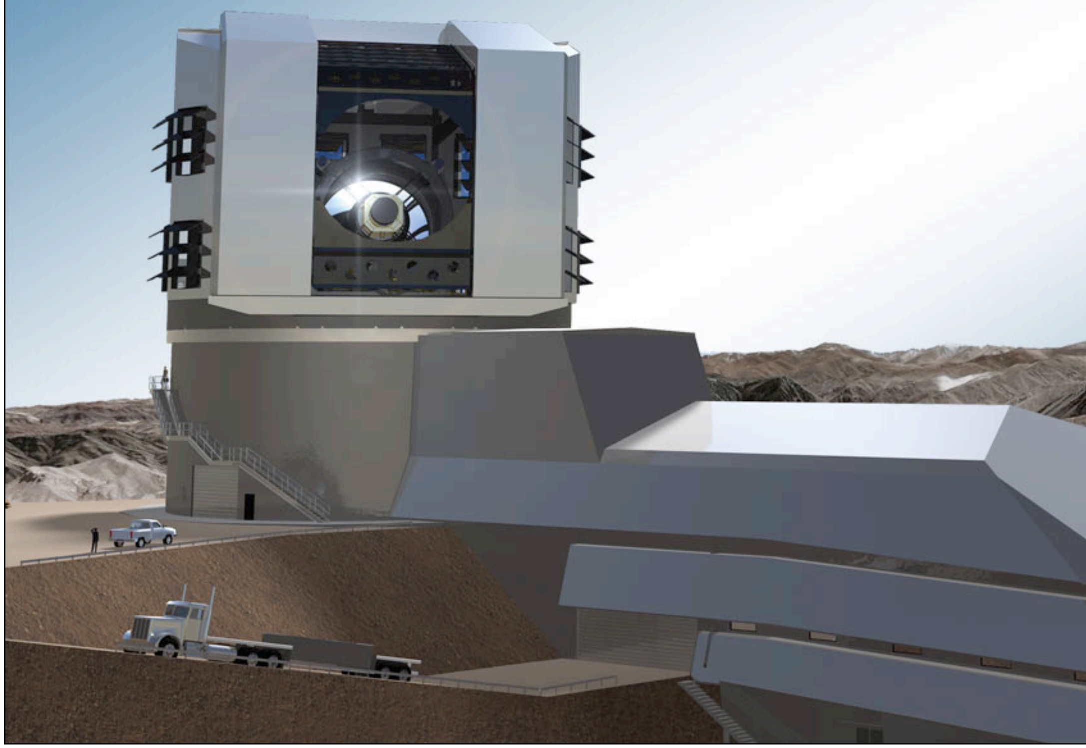
Analysis Coordinator and Photo-z Working Group co-convener, LSST Dark Energy Science Collaboration



- See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments* for more details!

It's nice to be back in the land of the bears...

Outline

- Review: LSST, DESI, and photometric redshifts
- Training photometric redshifts for DES and LSST
  - Potential systematics from training sets
- Another role for DESI: Supernova host redshifts
- Mitigating systematics: cross-correlation techniques for photo-z calibration
- The LSST Dark Energy Science Collaboration

- See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments* (http://arxiv.org/abs/1309.5384, 1309.5388) for much more!
  - Ask me about the Milky Way?

2 surveys I'll focus on today

- 8m diameter survey telescope, deep imaging in 6 filters (*ugrizy*)
- 10 sq. deg. FOV, cover visible sky every 3 nights
- 10-year total survey: extremely deep imaging over 20k square degrees
- Cosmology, Mapping the Milky Way, the Transient Universe, Inventory of the Solar System

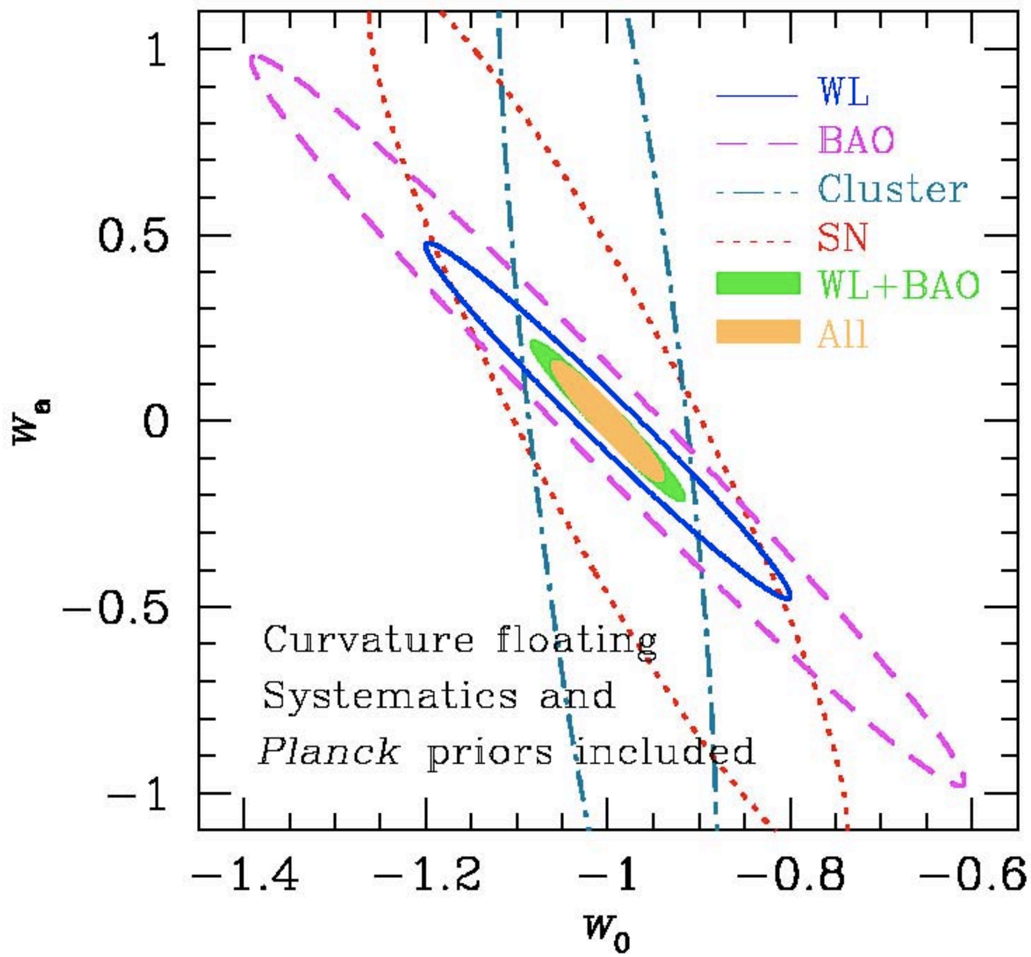
- Add new full-optical spectrograph to 4m Mayall telescope
- 5000 fibers, 7 sq. deg.
- BAO survey of ~20+million galaxies & QSOs, $0.5 < z < 3.5$, over ~14k square degrees
- Stage IV BAO

LSST constrains dark energy in many ways… all will rely on redshift information

- LSST will constrain dark energy via 4 major probes:
    - Weak gravitational lensing
    - Baryon Acoustic Oscillations
    - Type Ia supernovae
    - Cluster counts

    (Plus strong lensing, etc.)

- For all of these, we want to measure some observable as a function of redshift

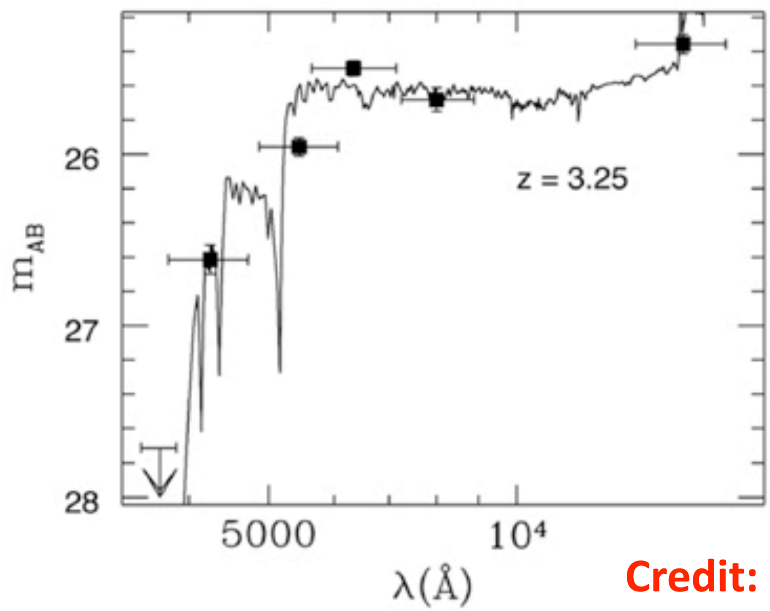


LSST Science Book

Spectroscopy provides ideal redshift measurements – but is infeasible for large samples

- At LSST "gold sample" (*i*<25.3) depths, ~180 hours on a 10m telescope to determine a redshift (70% of time) spectroscopically
- With a next-generation, 5000 fiber spectrograph on a 10m telescope, still >50,000 telescope-years to measure redshifts for LSST "gold" weak lensing sample (4 billion galaxies)!

- Alternative: use broad spectral features to determine *z* : a photometric redshift
- Advantage: high multiplexing
- Disadvantages: lower precision, calibration uncertainties

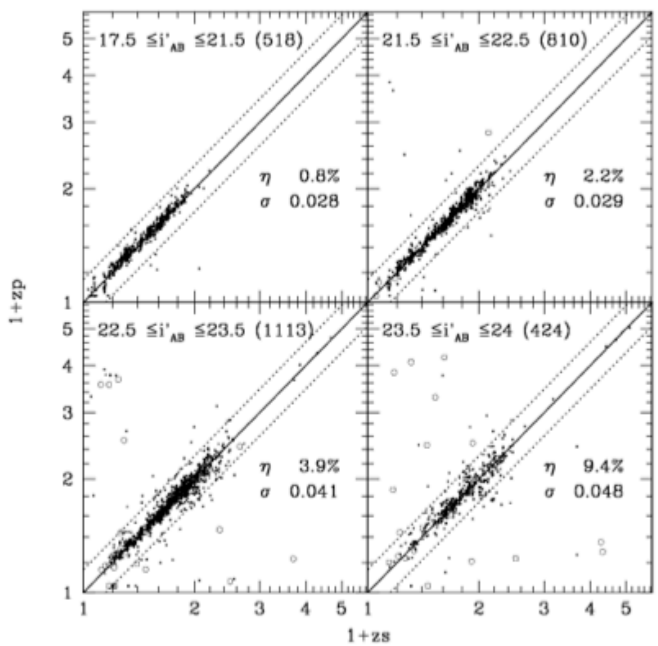


Credit: ESO

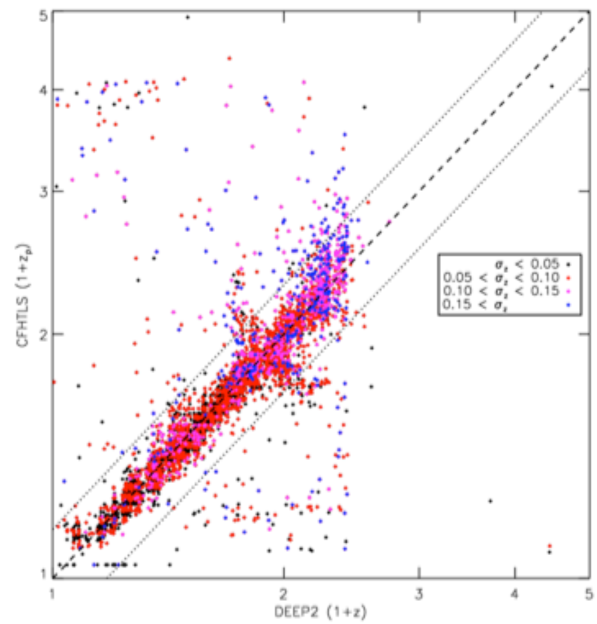
Two basic methods: Template fitting…

- **Use galaxies with known *z* to calibrate set of underlying galaxy spectral energy distributions (SEDs) and photometric band-passes**
  - **Determine posterior probability distribution for *z* | *ugrizy***
  - **Also provides info on galaxy properties from template fit**

Needs spectra of galaxies spanning full range of possible properties to tune templates, establish priors, etc.



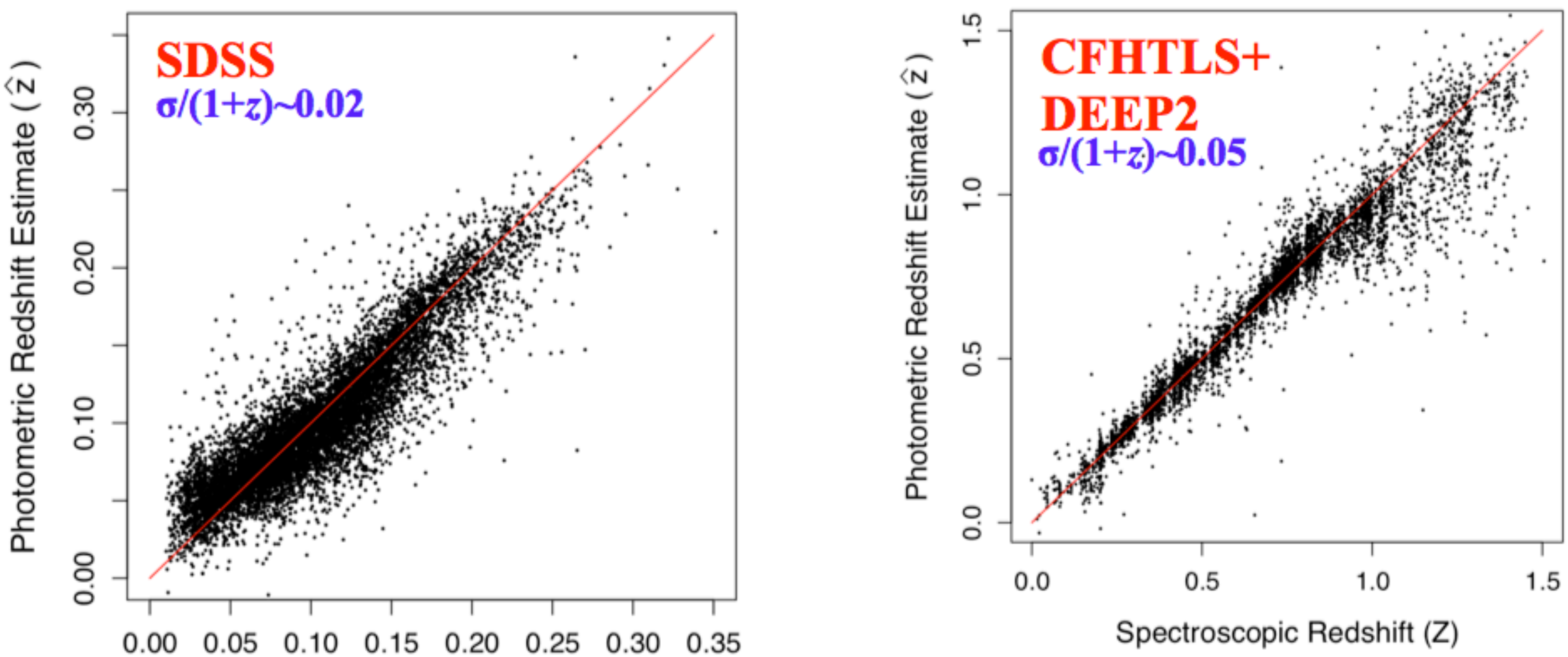
Ilbert et al. 2006



Ilbert photo-z's vs. DEEP2 *z*

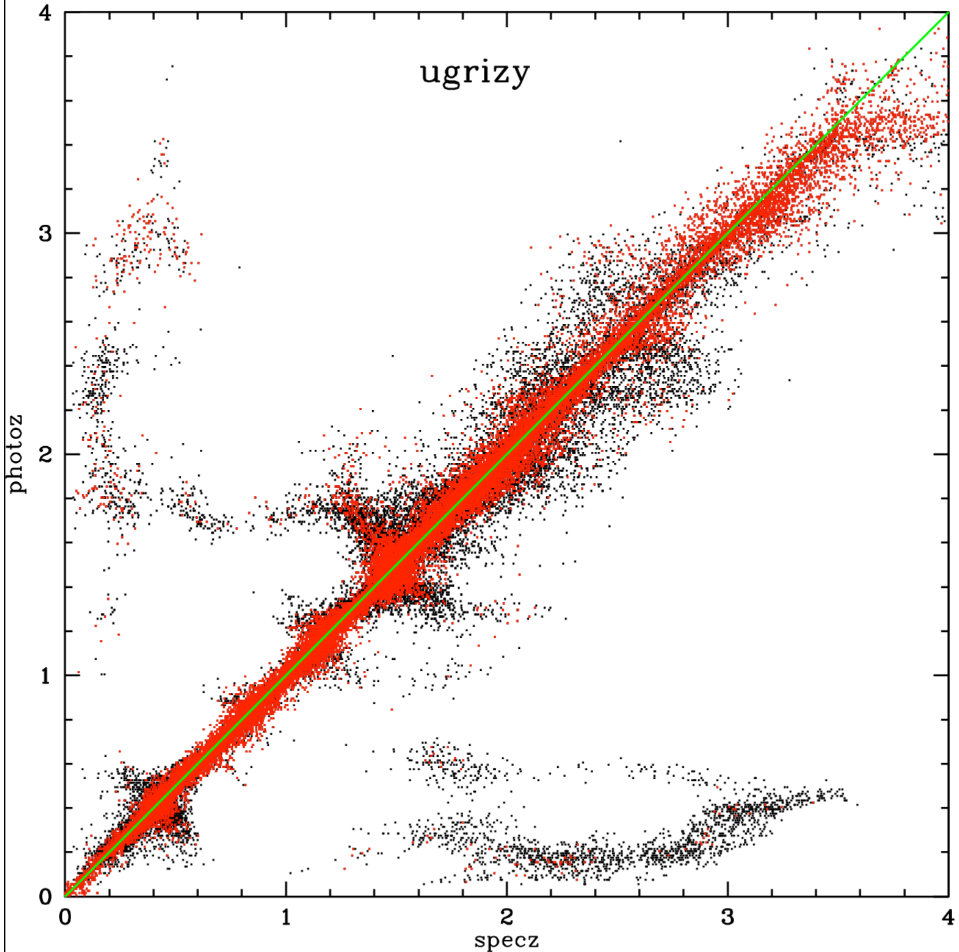
… and Training-Based Photo-z's

- Use galaxies with known redshift and uniform/well-understood sampling to determine a relationship between *z* and colors
- Training set MUST span full range of properties & z of galaxies
- Can take advantage of progress in machine learning & stats

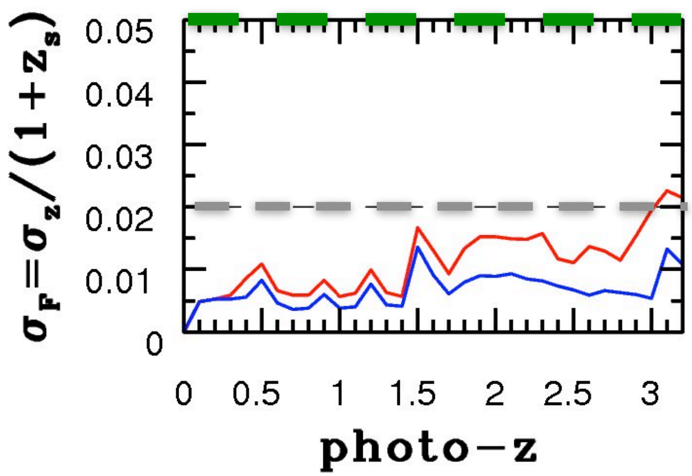


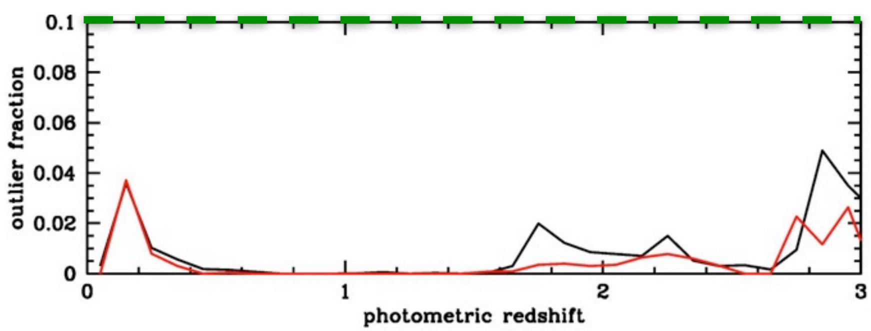
Freeman, JN et al. 2009

Example: expected photo-z performance for LSST *ugrizy*



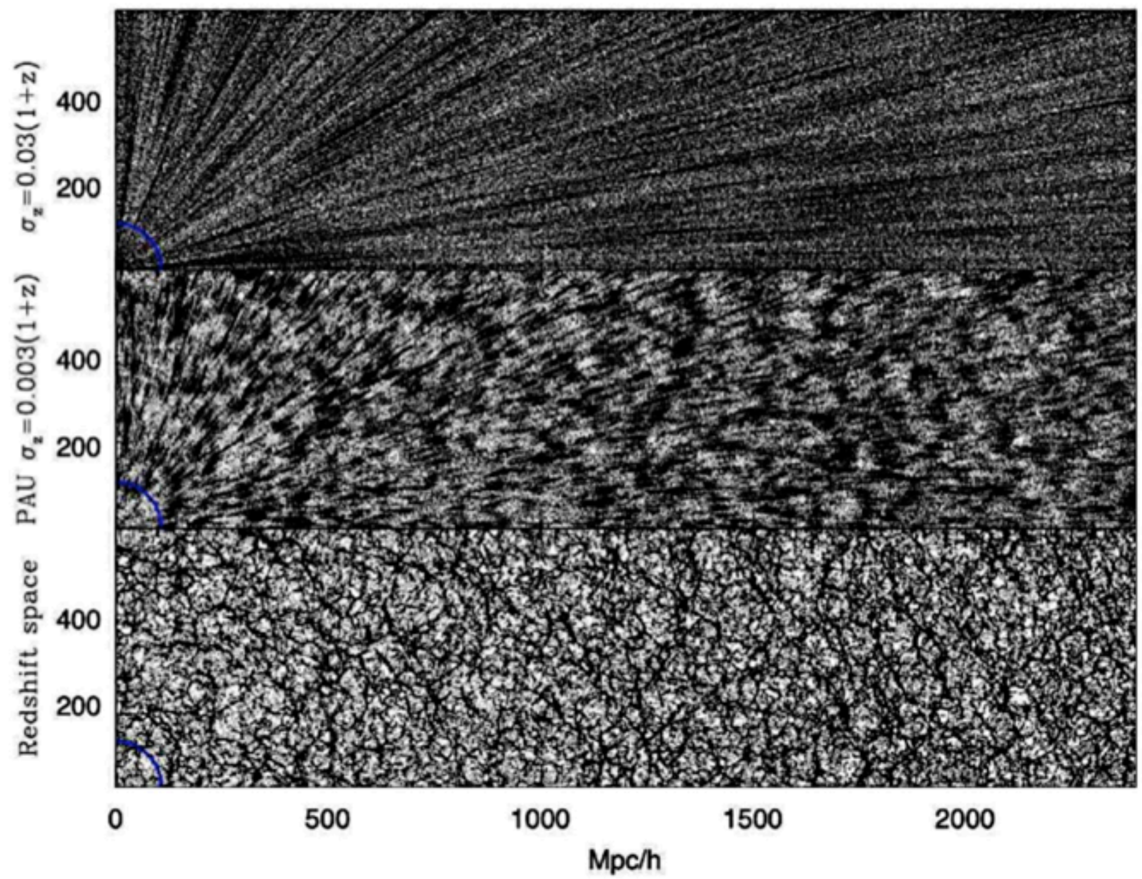
Green: Requirements on actual performance; grey: requirements on performance <u>with perfect template knowledge</u> (as in these sims)





Two spectroscopic needs for photo-z work: training and calibration

- Better training of algorithms using objects with spectroscopic redshift measurements shrinks photo-z errors and improves DE constraints, esp. for BAO and clusters



Benitez et al. 2009

  - Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.

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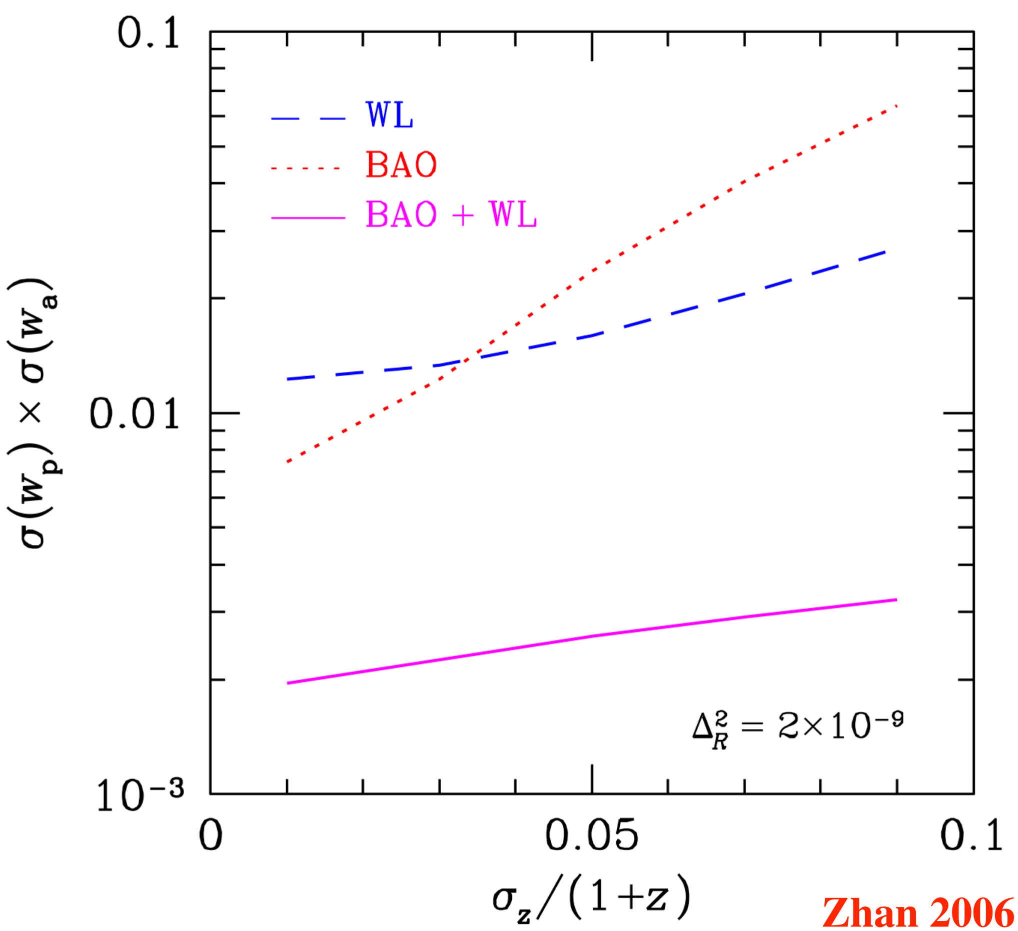
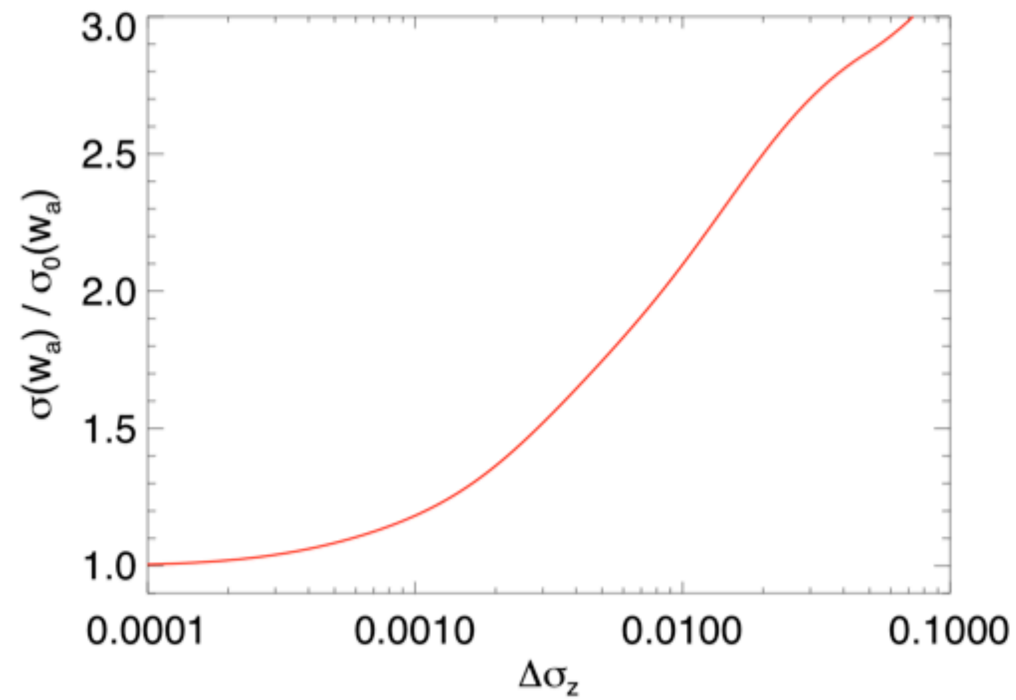


Zhan 2006

- **Training datasets will contribute to calibration of photo-z's. ~Perfect training sets can solve calibration needs.**

Two spectroscopic needs for photo-z work: training and calibration

- For weak lensing and supernovae, individual-object photo-z's do not need high precision, but the calibration must be accurate - i.e., bias and errors need to be extremely well-understood

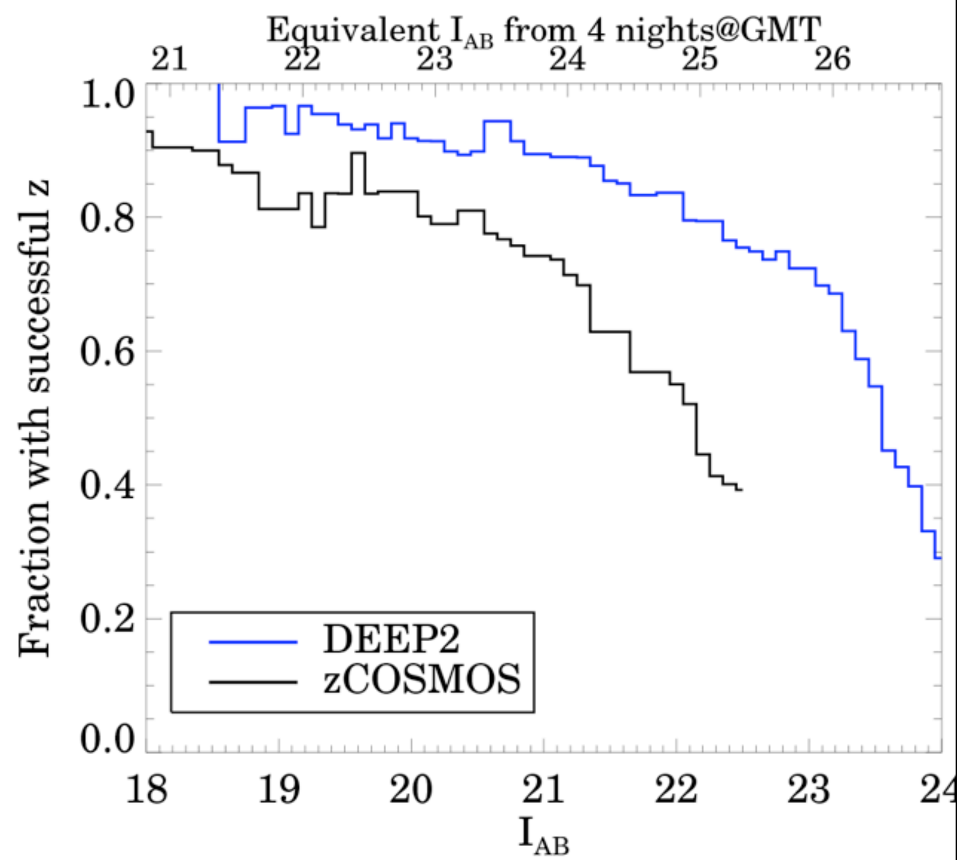


Newman et al. 2013

- *uncertainty in* bias, $\sigma(\delta_z) = \sigma(<z_p - z_s>)$, and in scatter, $\sigma(\sigma_z) = \sigma(RMS(z_p - z_s))$, must both be <~0.002(1+z) for Stage IV surveys

Biggest concern: incompleteness in training/calibration datasets

- In current deep redshift surveys (to i~22.5/R~24), 25-60% of targets fail to yield secure (>95% confidence) redshifts
- Redshift success rate depends on galaxy properties - losses are systematic, not random
- Estimated need 99-99.9% completeness to prevent systematic errors in calibration from missed populations

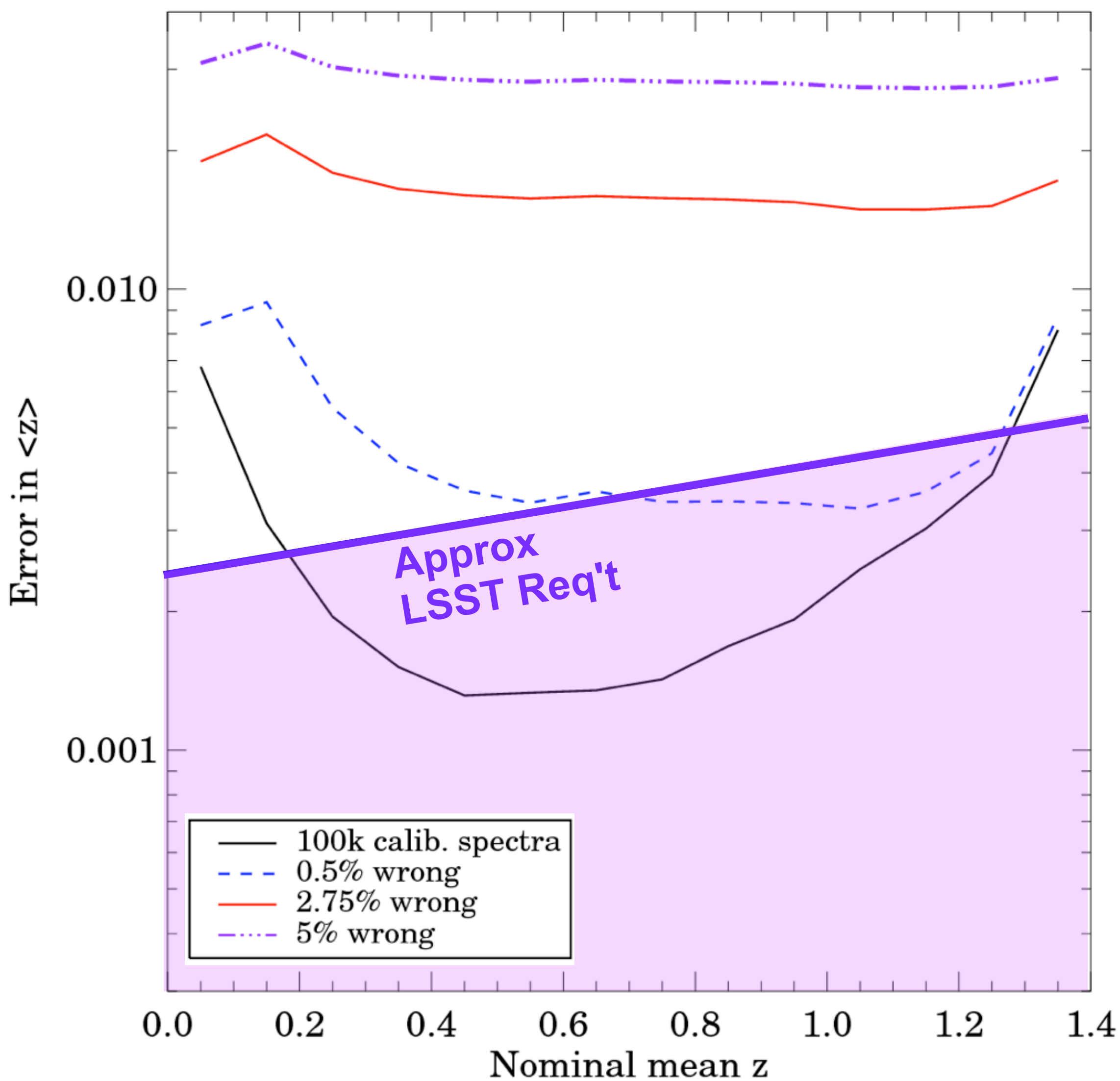


Data from DEEP2 (Newman et al. 2013) and zCOSMOS (Lilly et al. 2009)

Note: even for 100% complete samples, current false-z rates would compromise calibration accuracy

- **Only the highest-confidence redshifts should be useful for precision calibration: lowers spectroscopic completeness further when restrict to only the best**

Based on simulated redshift distributions for ANNz-defined DES bins in mock catalog from Huan Lin, UCL & U Chicago, provided by Jim Annis



Spectroscopic training set requirements

- Goal: make δ_z and $\sigma(\sigma_z)$ so small that systematics are subdominant
- Many estimates of training set requirements (Ma et al. 2006, Bernstein & Huterer 2009, Hearin et al. 2010, LSST Science Book, etc.)
- General consensus that roughly 20k-30k extremely faint galaxy spectra are required to characterize:
  - Typical z_{spec}-z_{phot} error distribution
  - Accurate catastrophic failure rates for all objects with $z_{phot} < 2.5$
  - Characterize all outlier islands in z_{spec}-z_{phot} plane via targeted campaign (core errors easier to determine)
- Those numbers of redshifts are achievable with GMT, if multiplexing is high enough

What qualities do we desire in our training sets?

- **Sensitive spectroscopy of faint objects (to i=23.7 for DES, 25.3 for LSST)**

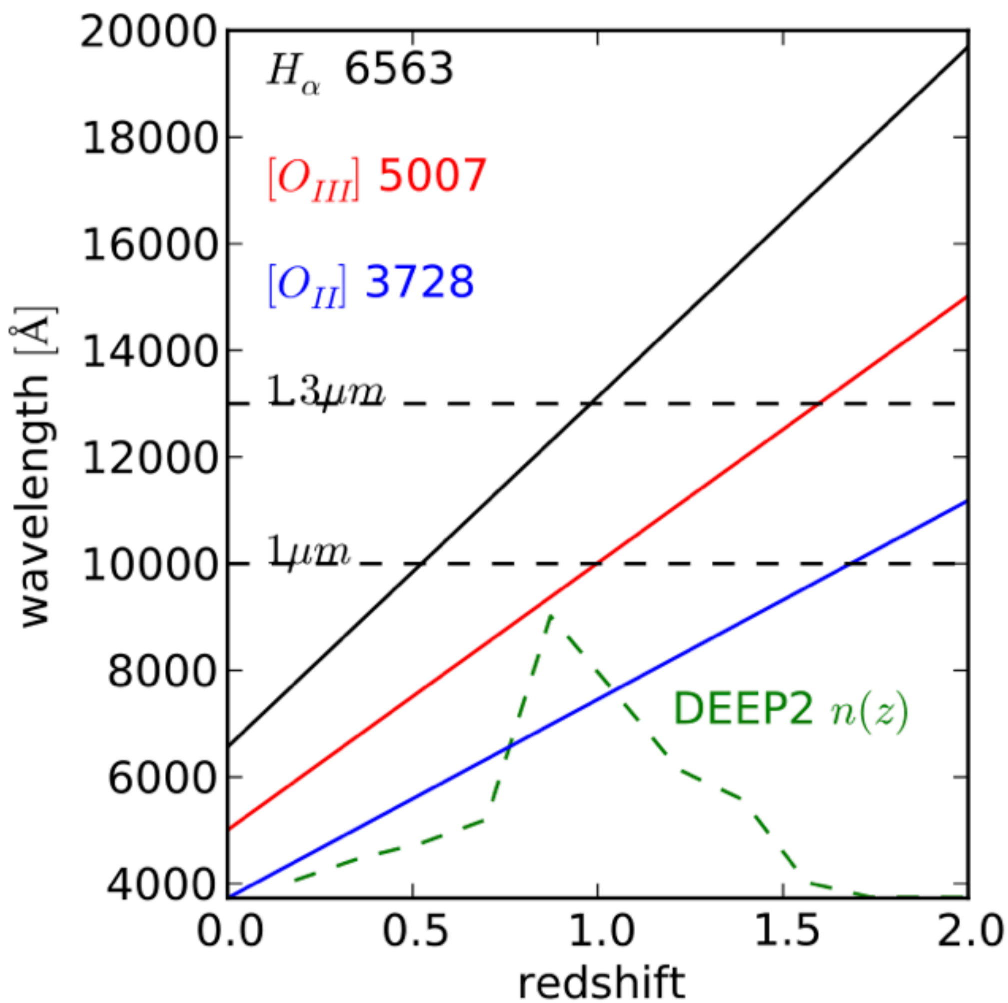
  - Need a combination of large aperture and long exposure times; >20 Keck-nights (=4 GMT-nights) equivalent per target, minimum

- **High multiplexing**

  - Obtaining large numbers of spectra is infeasible without it

What qualities do we desire in our training sets?

- **Coverage of full ground-based window**
  - **- Ideally, from below 4000 Å to ~1.5µm**
    - **- Require multiple features for secure redshift**

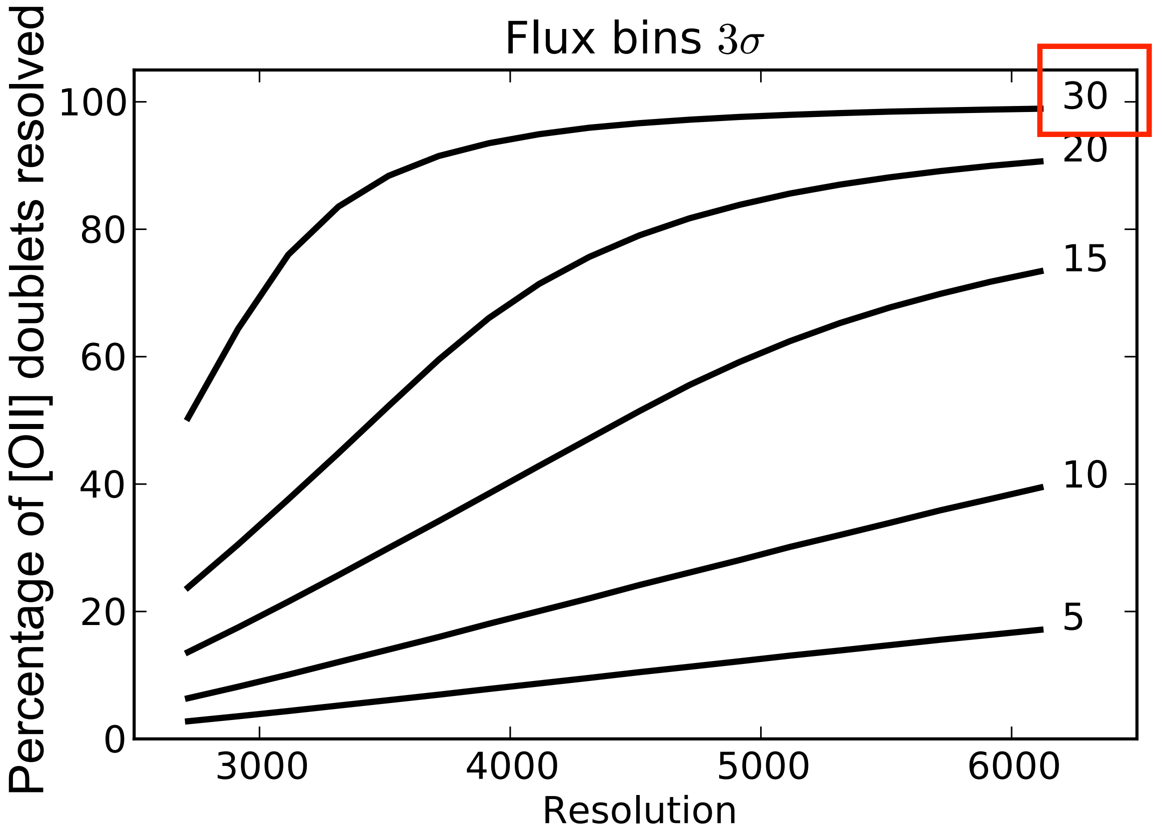


Comparat et al. 2013, submitted

What qualities do we desire in our training sets?

- **Significant resolution (R>~4000) at red end**

  - Allows redshifts from [OII] 3727 Å doublet alone, key at *z*>1



Comparat et al. 2013, submitted

What qualities do we desire in our training sets?

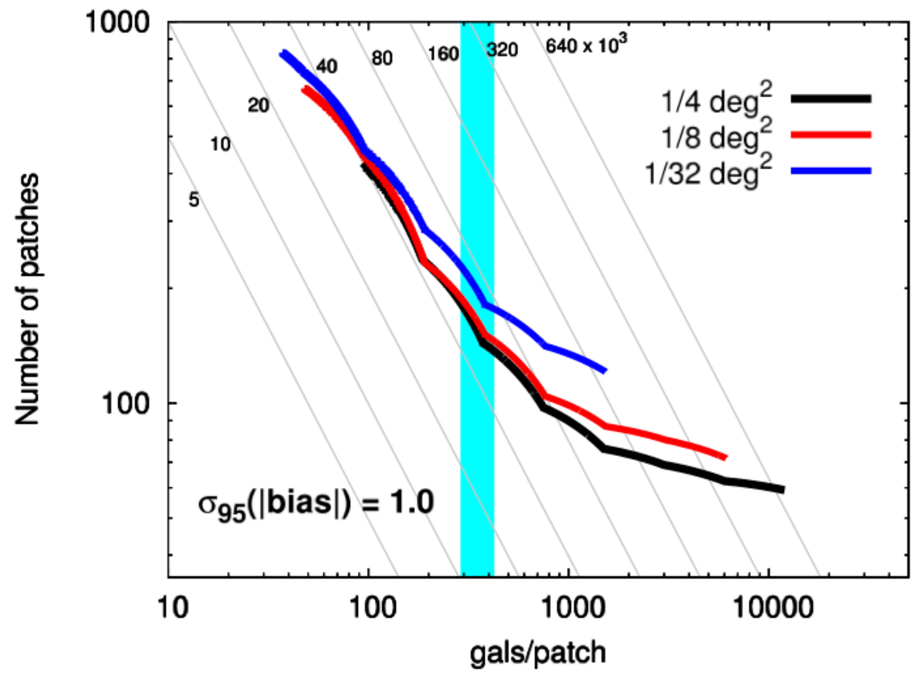
- **Field diameters > ~20 arcmin**

  - Need to span several correlation lengths for accurate clustering measurements (key for galaxy evolution science and cross-correlation techniques)

  - $r_0 \sim 5\ h^{-1}$ Mpc comoving corresponds to ~7.5 arcmin at z=1, 13 arcmin at z=0.5

- **Many fields**

  - Minimizes impact of sample/ cosmic variance.
    - e.g., Cunha et al. (2012) estimate that 40-150 ~0.1 deg^2 fields are needed for DES for sample variance not to impact errors (unless we get clever)



Cunha et al. 2012

Estimated time requirements for training sets

- DES / 75% complete:
  ➡ 0.05 - 0.45 years (c. 2018), 0.02+ years (c. 2022+)
- DES / 90% complete:
  ➡ 0.34 - 1.6 years (c. 2018), 0.13 years (c. 2022+)
- LSST / 75% complete:
  ➡ 1.1 - 5.1 years (c. 2018), 0.42+ years (c. 2022+)
- LSST / 90% complete:
  ➡ 6.9 - 32 years (c. 2018), 2.6+ years (c. 2022+)

Depending on telescope/spectrograph properties, time required is determined by # of fields (15), # of spectra observable simultaneously (if multiplexing is low), or telescope field of view (if <<20' diameter). See Tables 2-1 & 2-2 of white paper.

DESI for deep surveys

- Compare DESI vs Subaru/PFS:
  - 5000 fibers vs 2500
  - 4m aperture vs 8m
- Getting the same number of photons on the same number of objects will take ~2x longer survey time with DESI
  - >2x the observing time may be available!

Summary of potential instruments

Telescope / Instrument	Collecting Area (m^2)	Field area ($arcmin^2$)	Multiplex	Limiting factor
Keck / DEIMOS	76	54.25	150	Multiplexing
VLT / MOONS	58	500	500	Multiplexing
Subaru / PFS	53	4800	2400	# of fields
Mayall 4m / DESI	11.4	25500	5000	# of fields
WHT / WEAVE	13	11300	1000	Multiplexing
GMT/MANIFEST+GMACS	368	314	420-760	Multiplexing
TMT / WFOS	655	40	100	Multiplexing
E-ELT / OPTIMOS	978	39-46	160-240	Multiplexing

Table 2-1. *Characteristics of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Assuming that we wish for a survey of ~15 fields of at least 0.09 deg² each yielding a total of at least 30,000 spectra, we also list what the limiting factor that will determine total observation time is for each combination: the multiplexing (number of spectra observed simultaneously); the total number of fields to be surveyed; or the field of view of the selected instrument. For GMT/MANIFEST+GMACS and VLT/OPTIMOS, a number of design decisions have not yet been finalized, so a range based on scenarios currently being considered is given.*

Time required for each instrument

Telescope / Instrument	Total time(y), DES / 75% complete	Total time(y), LSST / 75% complete	Total time(y), DES / 90% complete	Total time(y), LSST / 90% complete
Keck / DEIMOS	0.51	10.22	3.19	63.89
VLT / MOONS	0.20	4.00	1.25	25.03
Subaru / PFS	0.05	1.10	0.34	6.87
Mayall 4m / DESI	0.26	5.11	1.60	31.95
WHT / WEAVE	0.45	8.96	2.80	56.03
GMT/MANIFEST+GMACS	0.02 - 0.04	0.42 - 0.75	0.13 - 0.24	2.60 - 4.71
TMT / WFOS	0.09	1.78	0.56	11.12
E-ELT / OPTIMOS	0.02 - 0.04	0.50 - 0.74	0.16 – 0.23	3.10 - 4.65

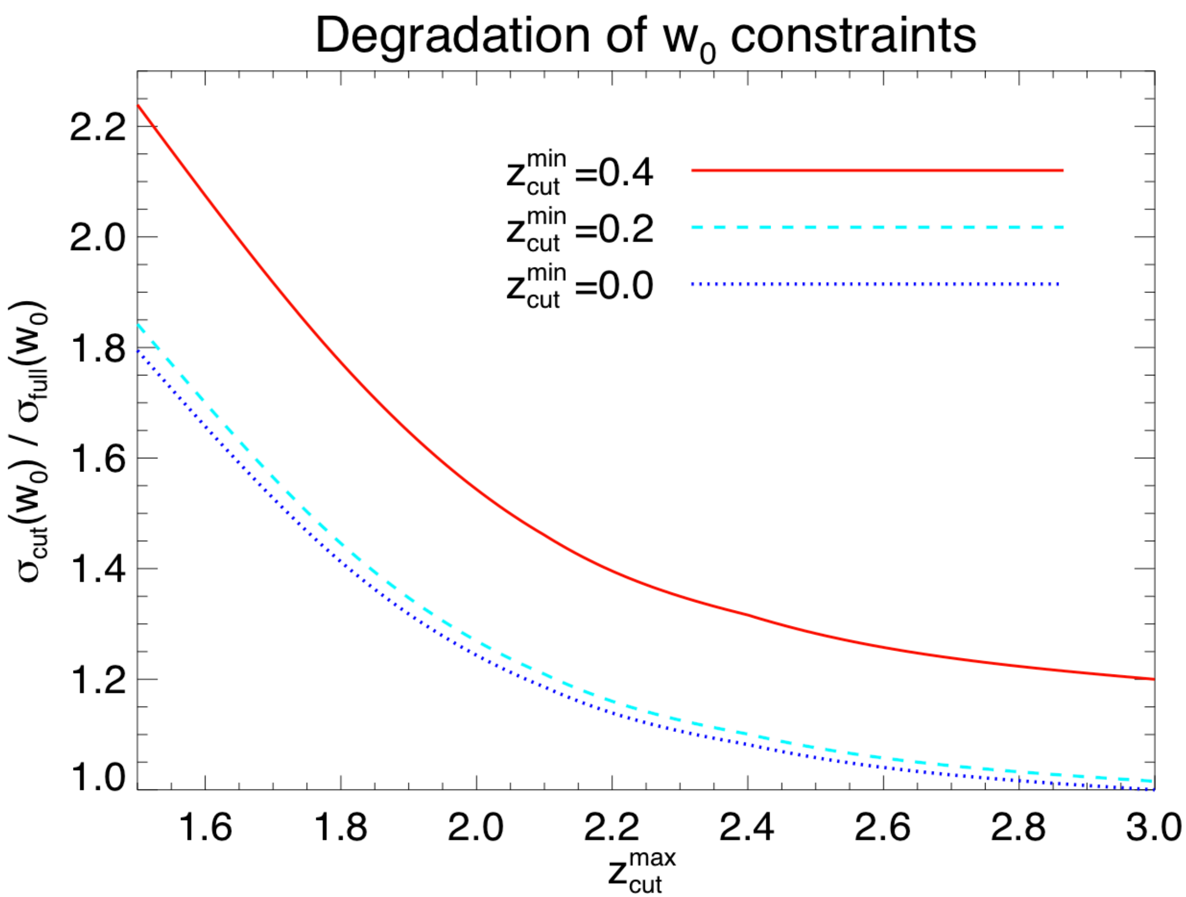
Table 2-2. *Estimates of required total survey time for a variety of current and anticipated telescope/instrument combinations relevant for obtaining photometric redshift training samples. Calculations assume that we wish for a survey of ~15 fields of at least 0.09 deg^2 each, yielding a total of at least 30,000 spectra. Survey time depends on both the desired depth (i=23.7 for DES, i=25.3 for LSST) and completeness (75% and 90% are considered here). Exposure times are estimated by requiring equivalent signal-to-noise to 1-hour Keck/DEIMOS spectroscopy at i~22.5. GMT / MANIFEST + GMACS estimates assume that the full optical window may be covered simultaneously at sufficiently high spectral resolution; in some design scenarios currently being considered, that would not be the case, increasing required time accordingly.*

DESI can otherwise hard projects 'easy'

- The most useful LSST supernovae will be those found in 20-30 repeatedly-imaged 'deep drilling' fields
- >30,000 SNe Ia spread out over 300 square degrees found over 10 years
- Mapping from Keck/DEIMOS experience, 8 hours on DESI should yield redshifts for ~70% of hosts to r~24
  - ~60 nights total on DESI to get redshifts for ~70% of the supernovae - allows typing and cosmological analyses
- This would take >600 nights with VLT/VIMOS, or >2000 nights with Keck/DEIMOS

3 Ways to address spectroscopic incompleteness for calibrations – all may be feasible

I. **Throw out objects lacking secure photo-*z* calibration**



- **ID regions in e.g. *ugrizy* space where redshift failures occurred**
- **Eliminating a fraction of sample has modest effect on FoM**
  - **- Not yet known if sufficiently clean regions exist**

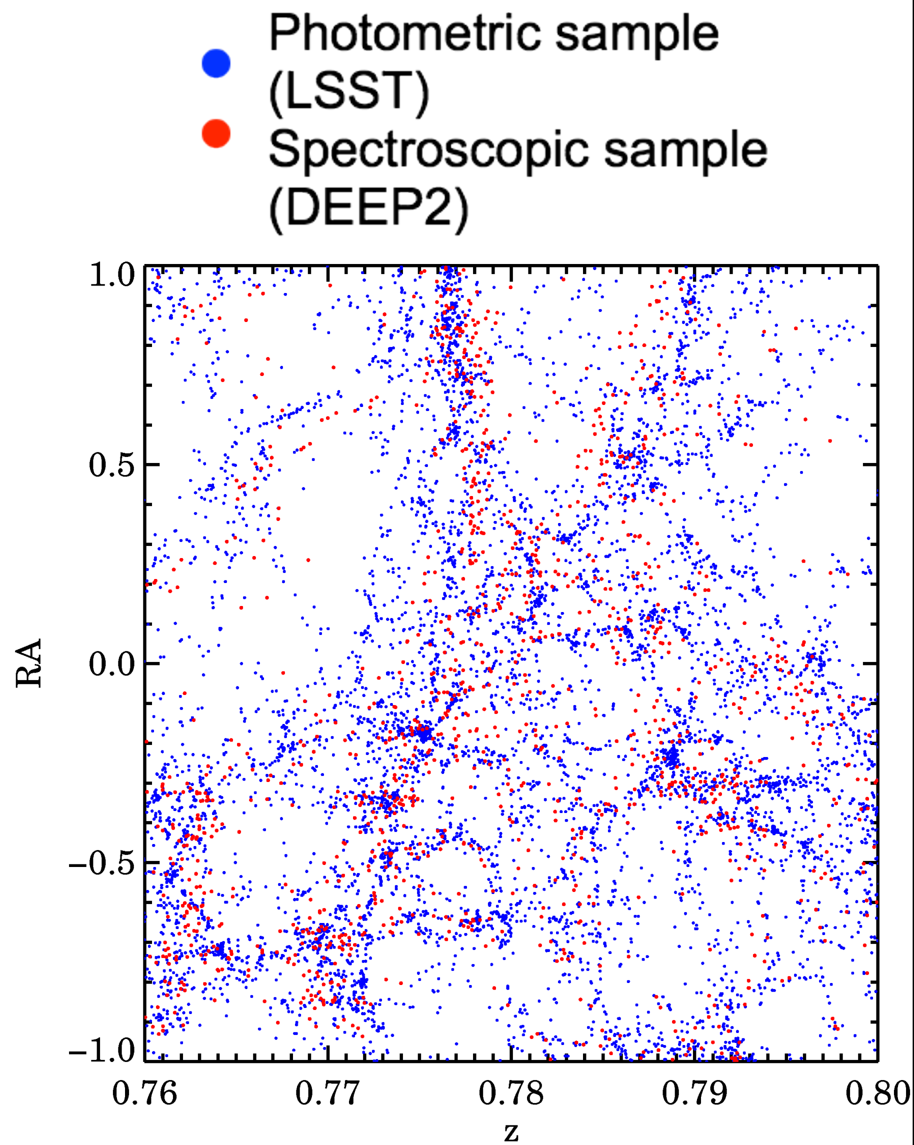
3 Ways to address spectroscopic incompleteness for calibrations – all may be feasible

II. Incorporate additional information
  - Longer exposure/wider wavelength range spectroscopy (JWST, etc.) for objects that fail to give redshifts in first try
    - Not yet known if will yield sufficient completeness
  - Develop comprehensive model of galaxy spectral evolution constrained by redshifts obtained
    - A major research program, not there now

III. Cross-correlation techniques

Cross-correlation methods: exploiting redshift information from galaxy clustering

- **Galaxies of all types cluster together: trace same dark matter distribution**
- **Galaxies at significantly different redshifts do not cluster together**
- **From observed clustering of objects in one sample vs. another (as well as information from autocorrelations), can determine the fraction of objects in overlapping redshift range**
- **Do this as a function of spectroscopic *z* to recover *p(z)***

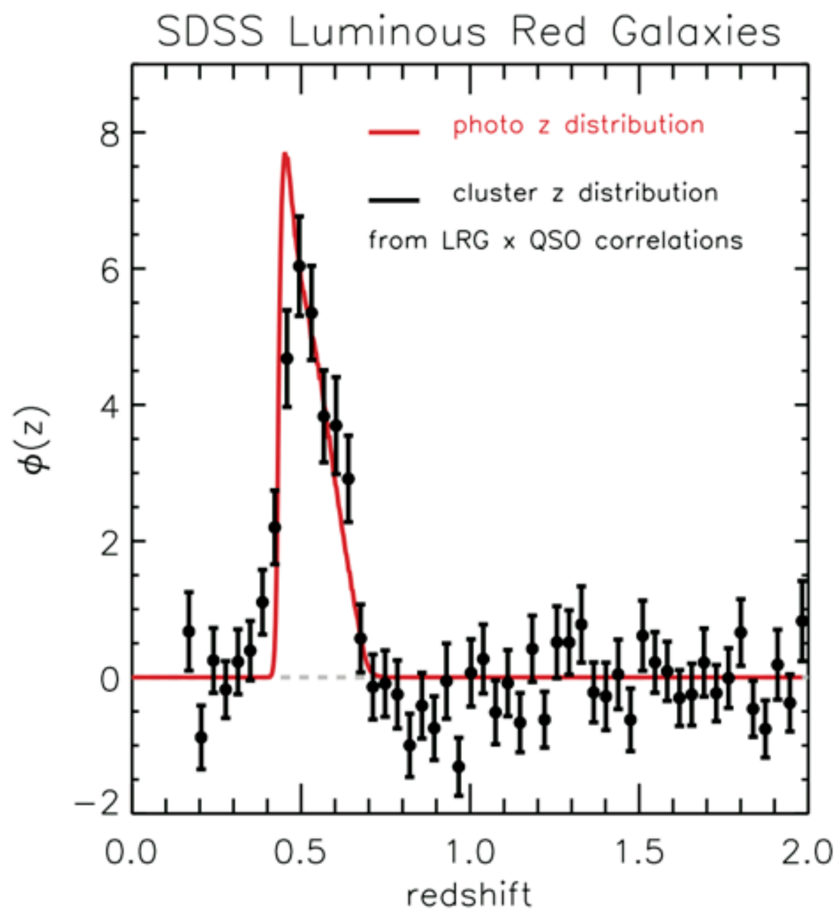


Higher-resolution information can be obtained by cross-correlating with spectroscopic samples

- Key advantage: spectroscopic sample can be systematically incomplete and include only bright galaxies!
- See: Newman 2008, Matthews & Newman 2010, 2011

Red: Photo-z distribution for LRGs in SDSS

Black: Cross-correlation reconstruction using only SDSS QSOs (rare at low z!)



Menard et al. 2013

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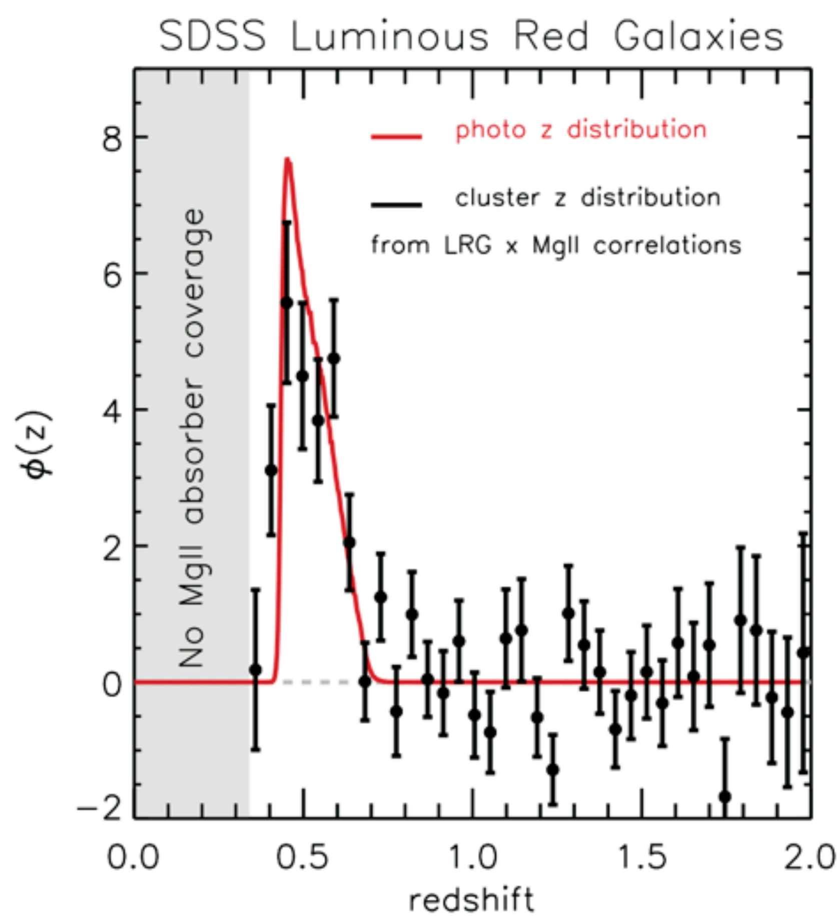
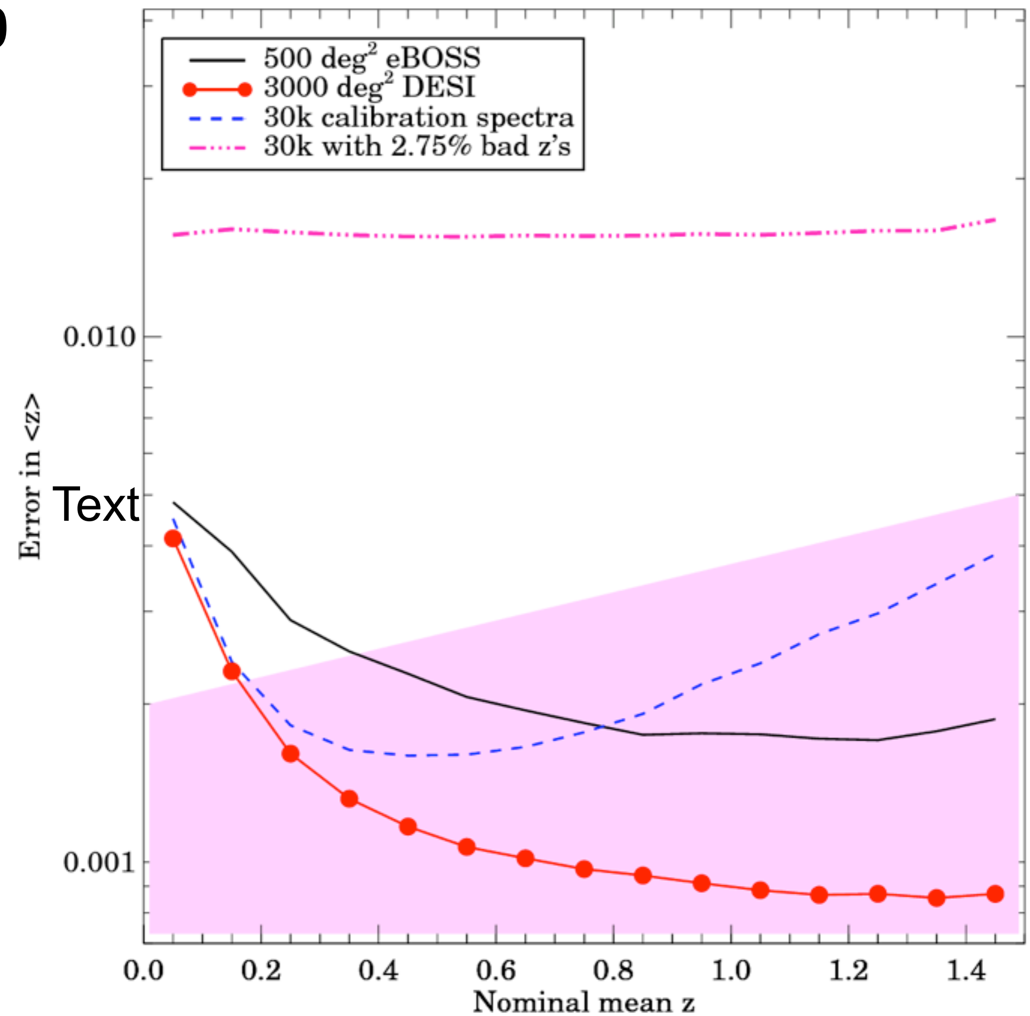


Menard et al. 2013

Spectroscopic requirements for cross-correlation methods

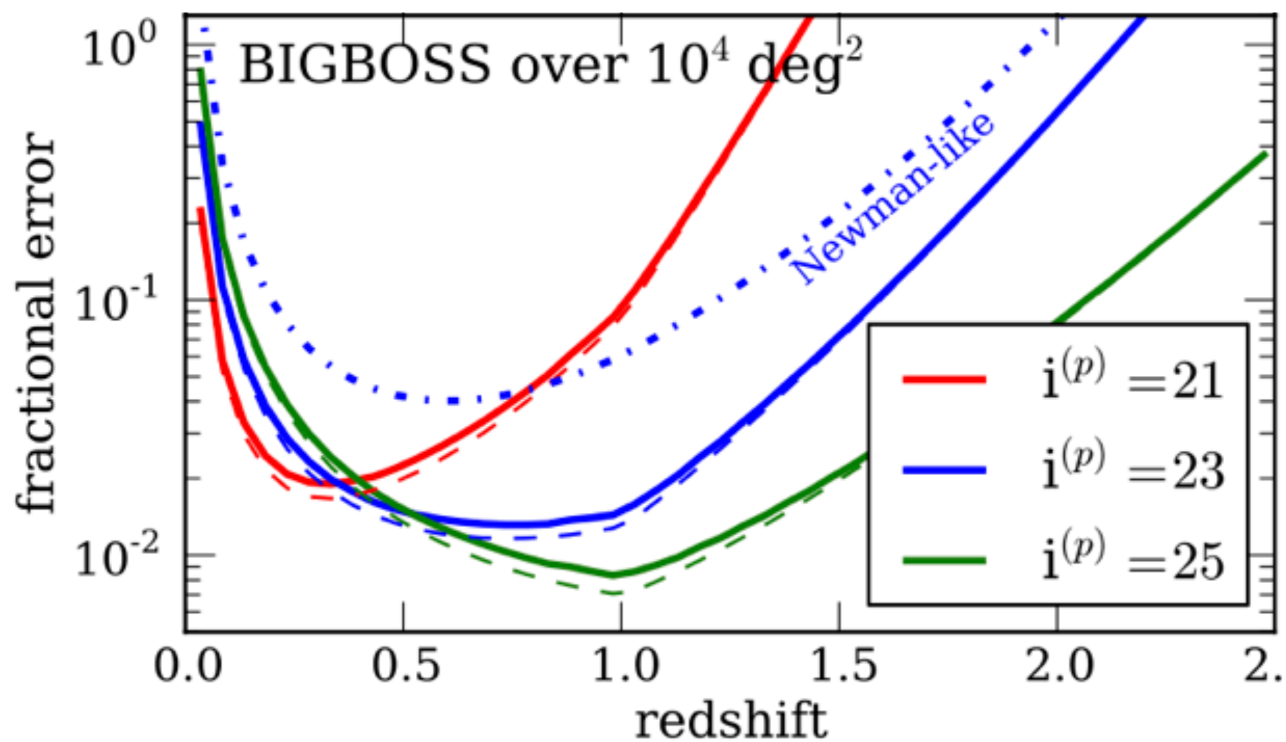
- Want >100k objects over >100 sq. degrees, spanning redshift range of photometric sample
- >500 square degrees of overlap with DESI-like survey sufficient for needs
- Expected ~3000 deg^2 overlap between DESI and LSST is comparable to 100% complete sample of 100k spectra with no false z's!
- The cross-correlations will simultaneously provide information on galaxy evolution



Snowmass White Paper: Spectroscopic Needs for Imaging DE Experiments

Those forecasts are pessimistic!

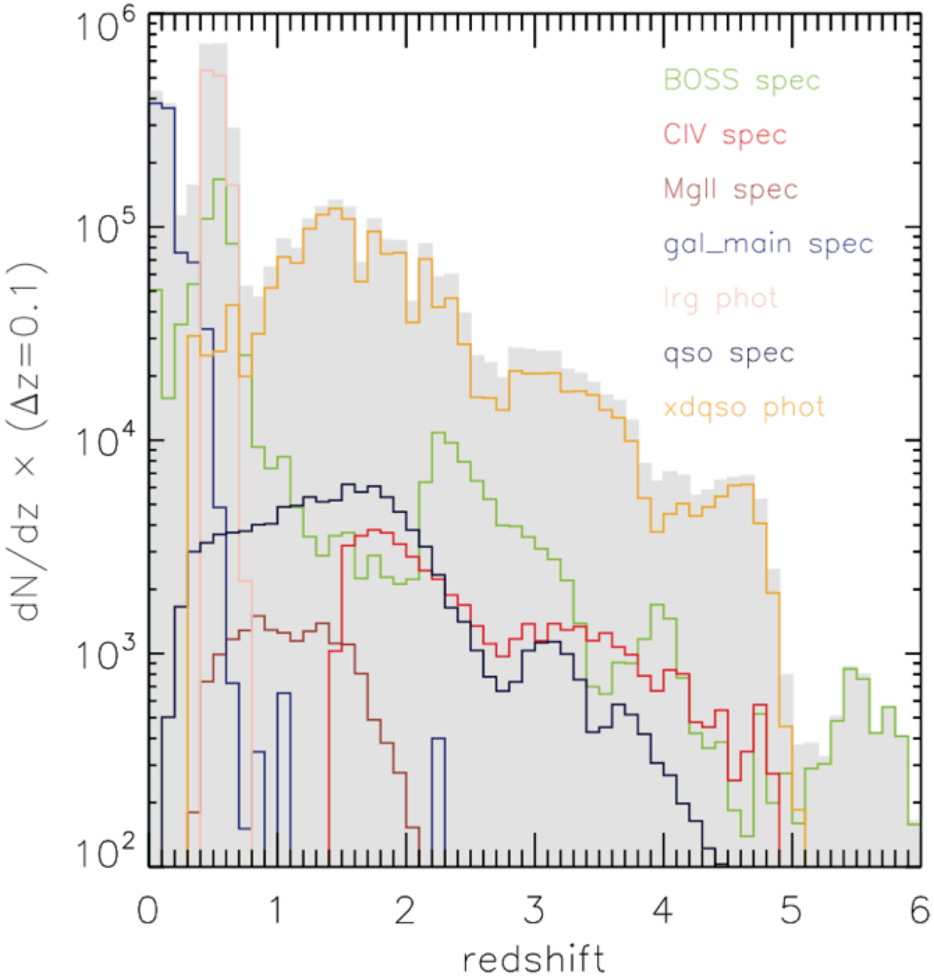
• McQuinn & White (2013): Application of optimal estimators to cross-correlation analysis

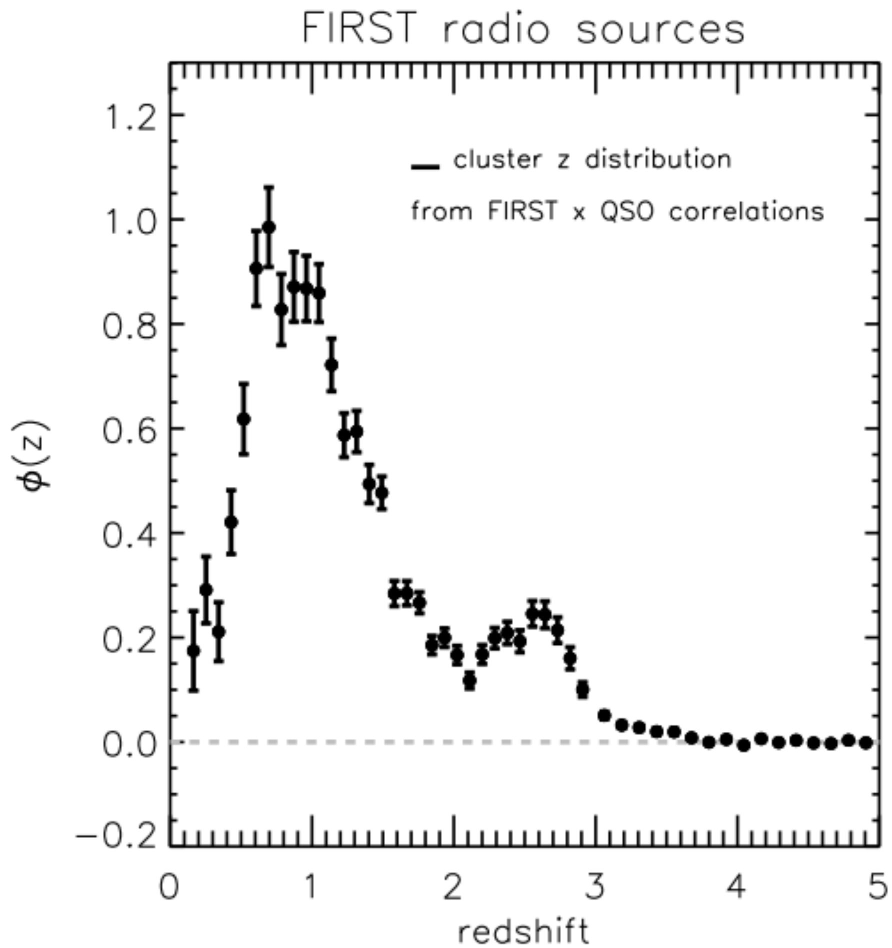


• Makes maximum use of information on linear scales, avoids integral constraint error

• Obtain errors 2-10x smaller than Newman 2008 / Matthews & Newman 2010

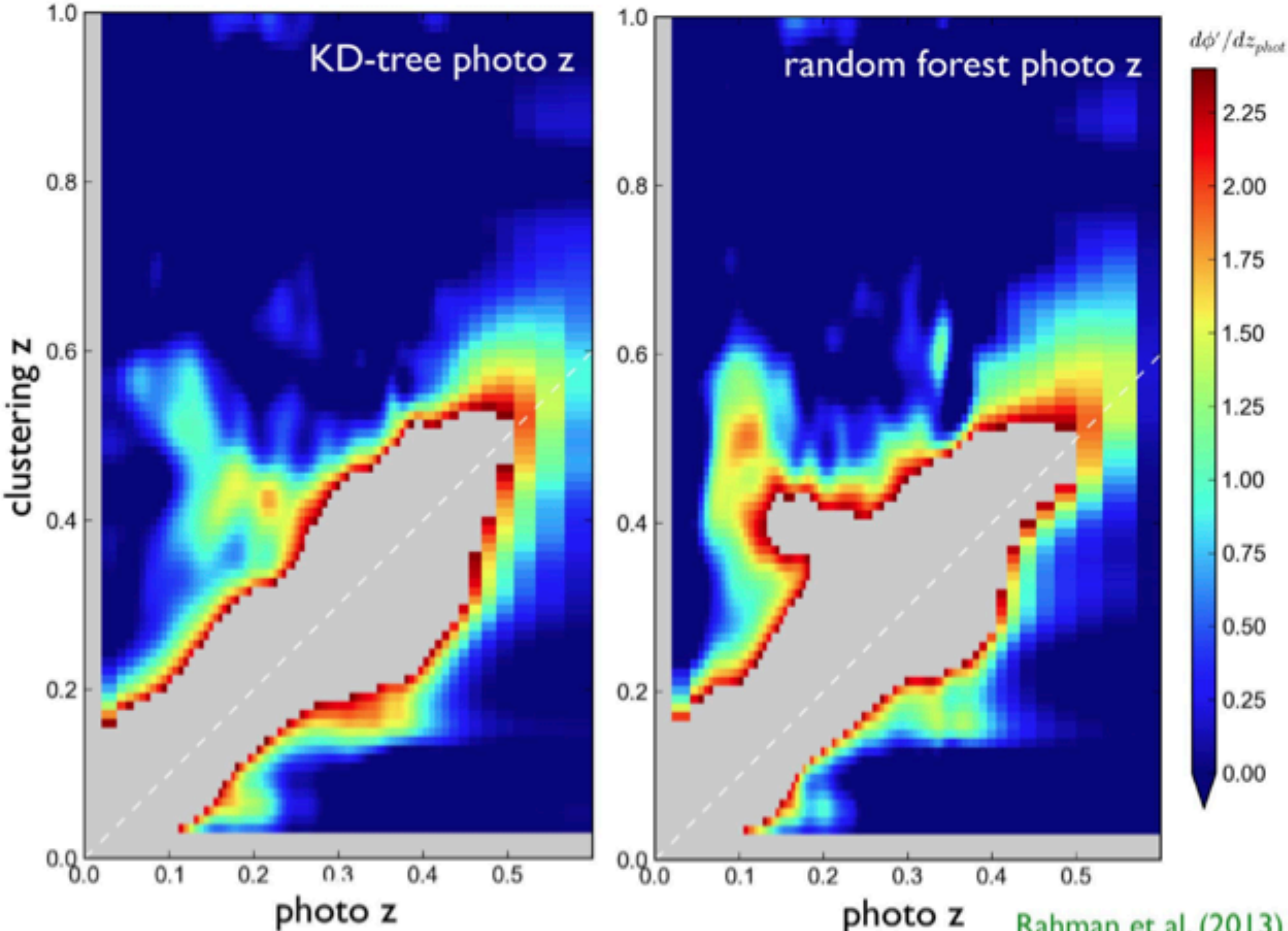
QSO samples are very useful at z>1: eBOSS and DESI will provide many





Menard et al. 2013

Cross-correlation methods are now being used to test SDSS photo-z's



Rahman et al. (2013)

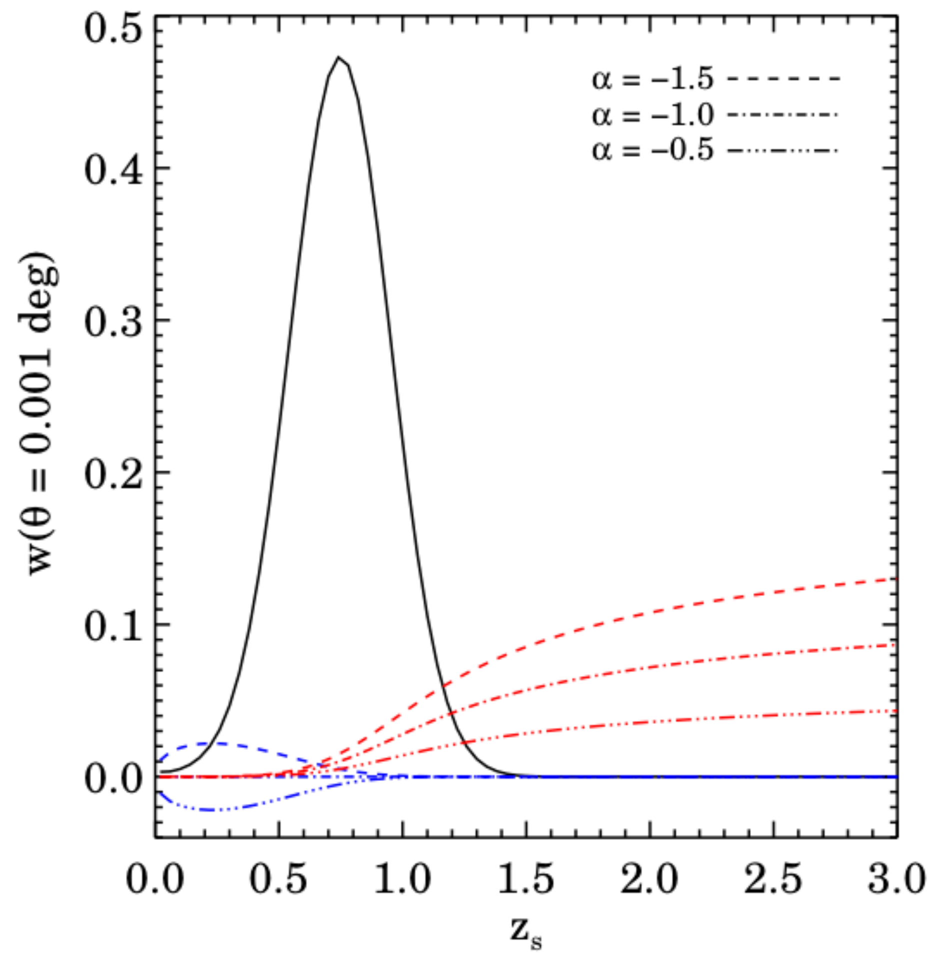
Biggest concern right now: disentangling cross-correlations from clustering and lensing magnification

- ***Black***: cross-correlations between photo-z objects (z=0.75 Gaussian) and spectroscopic sample as a function of *z*

- ***Blue***: observed cross-correlation due to spectroscopic objects lensing photometric ones

- ***Red***: observed cross-correlation due to photometric objects lensing spectroscopic ones

- **Weak/CMB lensing could help us predict the red curves**



Matthews & Newman 2014, in prep.

The LSST Dark Energy Science Collaboration

- **Founded summer 2012: want to make sure that we are ready to do dark energy science when LSST turns on c. 2022**

- **Spokesperson: Bhuvnesh Jain, U. Penn. Variety of working groups:**

- Analysis Working Groups
  1. Weak Lensing – Michael Jarvis, Rachel Mandelbaum
  2. Large Scale Structure – Eric Gawiser, Shirley Ho
  3. Supernovae – Alex Kim, Michael Wood-Vasey
  4. Clusters – Steve Allen, Ian Dell'Antonio
  5. Strong Lensing – Phil Marshall
  6. Combined Probes, Theory – Rachel Bean, Hu Zhan
  7. Photo-z Calibration – Jeff Newman (acting)

- Computing and Simulation Working Groups
  1. Cosmological Simulations – Katrin Heitmann
  2. Photon Simulator – John Peterson
  3. Computing Infrastructure – Richard Dubois
  4. Software – Erik Gottschalk

- Technical Working Groups
  1. System Throughput – Andrew Rasmussen
  2. Image Processing Algorithms – Robert Lupton
  3. Image Quality – Chuck Claver
  4. Science Operations and Calibration – Zeljko Ivezic

The LSST Dark Energy Science Collaboration

- Identified several dozen key tasks to begin the next few years
  - Many synergies with DES
  - See white paper at http://arxiv.org/abs/1211.0310
- Membership is open to those working on science/technical activities relevant to collaboration's goals
  - If this includes you, sign up at http://www.slac.stanford.edu/exp/lsst/desc/

Conclusions

- Photo-z's are critical for dark energy experiments
- Incompleteness or incorrect redshifts in spectroscopic samples will cause systematic errors in photo-z applications
- Cross-correlation methods can calibrate photometric redshifts even using incomplete samples of only bright galaxies & QSOs
- Minimum LSST photo-z training survey, ~75% complete:
  - 15 widely-separated pointings, ~30,000 spectra to *i* = 25.3, ~0.4 years on a 20-40m telescope (can do galaxy evolution science simultaneously)
- eBOSS and especially DESI are extremely useful for cross-correlation calibration
- See Snowmass white papers on *Cross-Correlations* and *Spectroscopic Needs for Imaging Dark Energy Experiments*, http://arxiv.org/abs/1309.5384, 1309.5388